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# **Performance of Band-Partitioned Canceller for a Wideband Radar**

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14. ABSTRACT  The performance of band-partitioned (BP) interference cancellation is investigated for a wideband (WB) radar. This report describes the trade-off studies carried out on the BP cancellers and identifies the techniques and parameters that are capable of improving cancellation performance as the radar bandwidth increases. It is found that the combined use of a proper number of subbands, subband filter weightings, data overlap, and sufficient degrees of freedom of the canceller system provide an excellent balance between processing complexity and performance for a WB BP canceller system. The effects of errors among various channels on adaptive cancellation resulting from filter mismatch and time difference due to multipath are evaluated. It is shown that performance degradation caused by filter mismatch errors can be compensated by increasing the number of subbands and the canceller degrees of freedom. The cancellation performance of a hybrid BP canceller consisting of band-partitioning and transversal filtering is also examined. The hybrid configuration with appropriately chosen time delays is found to be particularly effective in the presence of multipath, but at the expense of increasing system and processing complexity.					
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# **PERFORMANCE OF BAND-PARTITIONED CANCELLERS FOR A WIDEBAND RADAR**

## **INTRODUCTION**

An adaptive canceller combines the data in auxiliary channels with the data in a main channel so that the main channel output noise power residue is minimized. The main channel contains the desired signal and corruptive additive noise such as jamming. The desired signal is assumed to pass through the canceller undistorted. An effective way of eliminating unwanted data or noise from a main channel (the information channel) is by cancelling it with the correlated noise from auxiliary channels. After cancellation, there will be less corrupting noise in the main channel and the signal-to-noise power ratio is enhanced. In a digital canceller, the receiver system includes a chain for each channel containing radio frequency (RF) to intermediate frequency (IF) conversion with associated IF filtering, baseband conversion (low-pass (LP) filtering), and sample-and-hold (S+H) analog-to-digital (A/D) conversion, as shown in Fig. 1. Mismatch errors of any kind among channels of an adaptive canceller can reduce the achievable cancellation performance. These mismatch errors may consist of small time-delay differences, in-phase (I) and quadrature-phase (Q) imbalances, sampling errors, and filter frequency mismatch errors among various channels. If any link of this chain is not identical across the channels, then the mismatch errors will cause degradation in canceller performance.

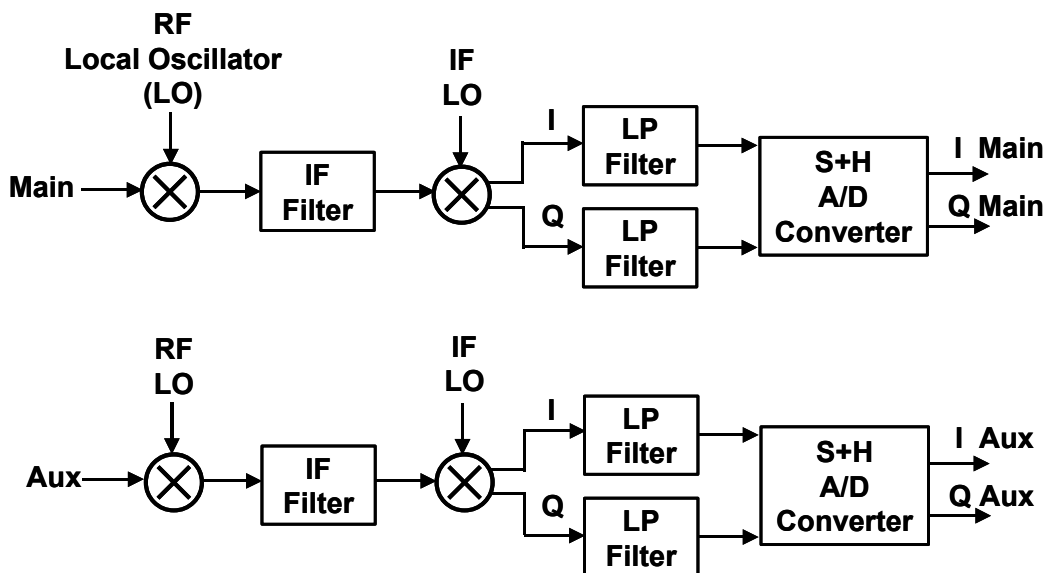


Fig. 1 – RF to IF to baseband to S+H to A/D conversion chain for main and auxiliary channels

Multiple adaptive weighting systems have been proposed over the years to improve canceller performance. Among them is the band-partitioning filter approach employing discrete Fourier transform (DFT) [1-3]. The main and auxiliary channels are each first identically filtered into a number of contiguous subbands. Cancellation is achieved on the associated subbands of the main and auxiliary channels. Finally, the residues from each subband are summed to yield a final residue. Since the auxiliary channels receive noise that is correlated with the corrupting noise in the main channel, it is possible to perform noise cancellation between the main and auxiliary channels.

A performance comparison investigation has been carried out for two multiple-weight adaptive canceller techniques: the DFT band partitioning approach and the transversal filter canceller approach [2]. It was found that the transversal filtering generally provides better performance for the same number of degrees of freedom in the presence of certain types of mismatch errors. For other types of mismatch errors among the channels, however, there was essentially no difference in performance between the two approaches.

In this report we investigate the performance of the band-partitioned (BP) canceller system and identify the techniques and parameters that are able to provide improved cancellation performance in the presence of mismatch errors as the radar bandwidth increases. These mismatch errors include those caused by time-delay differences and filter mismatches in the receiver chains (Fig. 1). In Section II, a generic BP canceller system describing the building blocks of the system is presented. Section III discusses the factors affecting the system performance for a wideband (WB) radar and a hybrid configuration consisting of band partitioning and transversal filtering is suggested for improving the canceller performance. Section IV presents the performance results of the WB system considering the effects of various parameters and compares them with the narrowband (NB) system. In Section V, the hybrid configuration is investigated in detail and its cancellation performance improvement is assessed for both NB and WB systems. Section VI contains the conclusions obtained regarding the performance of the WB BP canceller system and the hybrid configuration.

## BACKGROUND

The configuration of a typical BP canceller is described here. The building blocks of the BP system include the basic two-input canceller, the Gram-Schmidt canceller (GSC), and the process of subbanding. Kretschmer and Lewis [4] were the first to suggest an all-digital open-loop implementation. The basic module *C* for the digital system in this study consists of the open-loop canceller, as shown in Fig. 1. It computes the optimum weight based on range-sample averaging of the correlation between the input signals in the module's main (*M*) and auxiliary (*A*) channels. This optimum weight *W* is given by  $W = \frac{\overline{MA^*}}{\overline{AA^*}}$ , where \* denotes conjugation, and the bar denotes averaging which is performed using a finite number of time samples after A/D conversion in the main and auxiliary channels [4]. The minimum residue *R* of jamming power can be obtained by subtracting the optimum weight multiplied by the auxiliary channel signal from the main channel signal as  $R = M - WA$  (Fig. 2).

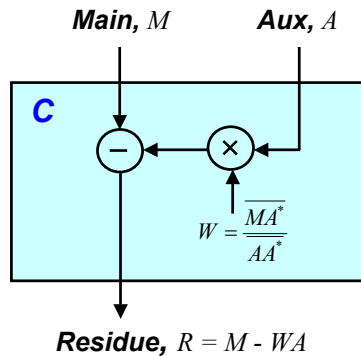


Fig. 2. Basic two-input decorrelation processor or canceller.

For degrees of freedom greater than two, the open-loop modules are configured as a Gram-Schmidt canceller (GSC). As an example, Fig. 3 shows the GSC with three input auxiliary channels. Each open-loop canceller has its local main and auxiliary inputs, shown by inputs to the top and the sides

of the blocks, respectively. Note that the correlation of the signals from external interfering sources relies on the correlation of simultaneously received signals in the main and auxiliary channels. The canceller operates so as to decorrelate the auxiliary inputs one at a time from the other inputs by use of the basic two-input canceller shown in Fig. 2. In the GSC as illustrated in Fig. 3,  $Aux_3$  is decorrelated with  $Main$ ,  $Aux_1$ , and  $Aux_2$  in the first level of decomposition. Next, the output channel that results from decorrelating  $Aux_3$  and  $Aux_2$  is decorrelated with the other outputs of the first-level cancellers. The decomposition proceeds until a final output channel is generated.

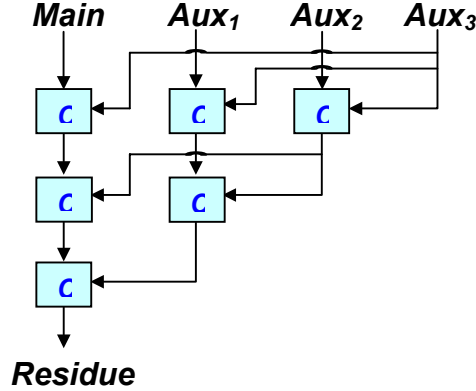


Fig. 3. Gram-Schmidt canceller with three auxiliary channels.

In a BP canceller system, the radar bandwidth is partitioned into subbands. The band partitioning is achieved by using an  $N$ -point fast Fourier transform (FFT), possibly weighted to reduce sidelobe levels, to create  $N$  subbands, with the cancellation performed within each subband. Figure 4 shows the BP canceller system with a single auxiliary channel. First,  $N$  subbands are generated by taking an FFT of the  $N$ -point block of input data in each channel. The subbands are denoted as  $Y_i$  for the main channel and  $X_i$  for the auxiliary channel, where  $i = 1, 2, \dots, N$ . Subsequent  $N$ -point data blocks are processed in the same manner to generate a stream of fast Fourier transformed incoming data. Residue  $r_i$  is then obtained for the  $i^{\text{th}}$  subband using the basic two-input canceller (Fig. 2) with finite time-sample averaging. Finally, the BP canceller output is obtained by taking the inverse FFT (possibly de-weighted) of the residues of the  $N$  subbands.

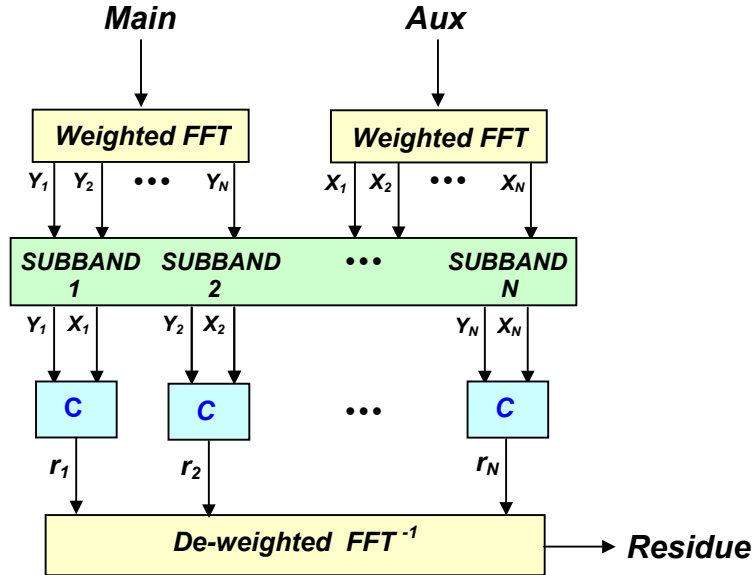


Fig. 4. A BP canceller system with single auxiliary input.

The BP canceller system with  $L$ -auxiliary channels is shown in Fig. 5. Similar to the single auxiliary BP canceller system,  $N$  subbands in each channel are first generated. However, the  $i^{\text{th}}$  component of the weighted  $N$ -point FFT of the main and  $L$  auxiliary channels forms the inputs to the GSC, instead of the basic two-input canceller as in the single auxiliary system. Processing the subsequent blocks of  $N$ -point data in each channel produces a stream of data for each subband. For the  $i^{\text{th}}$  subband the cancellation performed for the GSC with  $L+1$  inputs and finite time-sample averaging generates the residue  $r_i$ . The resultant output residues of the BP canceller are obtained by taking the de-weighted  $N$ -point inverse FFT of the GSC outputs  $r_i$ ,  $i = 1, 2, \dots, N$ , from the  $N$  subbands.

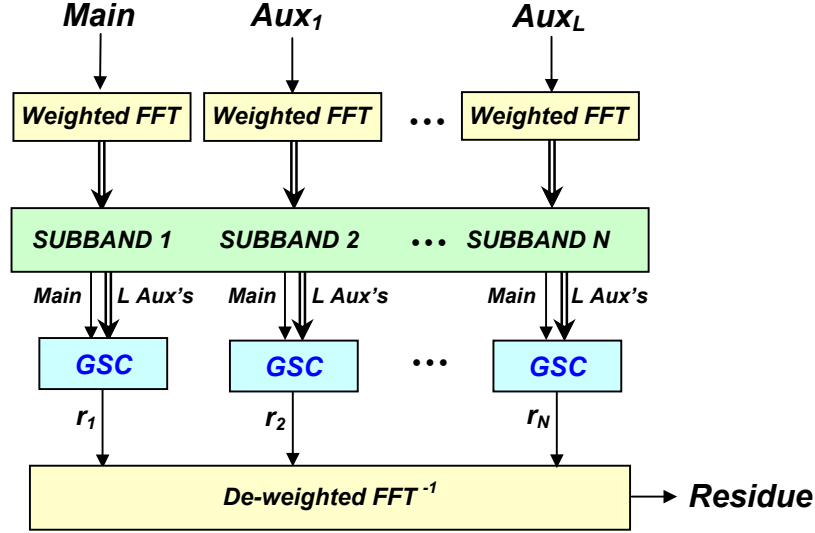


Fig. 5. A BP canceller system with  $L$  auxiliary inputs.

## WIDEBAND RADAR BAND-PARTITIONED CANCELLER

The performance of the BP canceller is investigated for a wide bandwidth system. The employment of BP processing permits frequency-dependent amplitude and phase adjustments to be made on the adaptive weights. The frequency-dependent mismatch compensation by means of BP processing is addressed here, which is important if a practical BP canceller design for a wideband radar is to be realized.

In practice, the electrical characteristics of each channel in the BP canceller are slightly different, leading to channel mismatches which may cause severe degradation in canceller performance. Two types of mismatch errors among the receiver channels are considered here: filter mismatch errors and differential time delays. Signals received on the main and auxiliary channels are normally filtered. The bandwidth of these filters is set equal to the bandwidth of the desired signal. Because of inaccuracies in the filter synthesis process, the poles and zeros of the frequency transfer functions will not be as designed and will have small perturbations around the desired poles and zeros. In this study we assume that the desired transfer function is a Butterworth filter, which is of much interest because it is easily synthesized. Note that by increasing the order of the Butterworth filter, the skirts of the LP filter become more attenuated. To compromise between filter characteristics and synthesis complexity, Butterworth filters of order 10 are adopted here for all canceller performance evaluations. The filter mismatch errors of the receiver channels are thus modeled as perturbed 10-pole Butterworth filters. The perturbed Butterworth filters are obtained by randomly perturbing the pole positions of these filters [5,6]. The perturbation consists of a two-dimensional zero-mean, uncorrelated Gaussian distribution at each pole position whose variance is specified as a percentage of the pole amplitude. The other mismatch error considered in this

study is the differential time delays caused by different propagation paths (multipath delay) among the canceller channels. In the simulation, the noise samples are re-sampled at a higher rate, then shifted by the appropriate time delay followed by down-sampling.

Multiple-channel BP canceller configurations are used to calculate the results presented in this report. The cancellation performance is measured by the cancellation ratio (CR), which is defined as the ratio of the main channel input signal power to the residue power with the desired signal undisturbed. Effects of various parameters and their interactions on the WB BP canceller system are investigated. In the study, several input weightings are applied to the subbands to achieve better canceller performance. The effects of radar bandwidth, sampling interval, time difference due to multipath, and channel mismatch characterized by the 10-pole Butterworth filter pole errors are evaluated for the BP canceller system. Trade-off studies are also conducted with respect to the number of subband filters and the number of canceller channels as the radar bandwidth increases. In addition, a hybrid system consisting of BP and transversal filtering is investigated. The performance improvement of the hybrid configuration over the regular BP canceller is evaluated for both NB and WB radar systems. The investigations are performed for both one- and two-jammer cases.

## PERFORMANCE RESULTS

The decorrelation weights associated with each two-input canceller are estimated using finite averaging. In this report, we present a pipeline processing “sliding window” architecture for implementing a multiple-channel BP canceller. With sliding-window processing schemes, the adaptive weights are updated by each set of new input data from the blocks of main and auxiliary channels that is presented to the BP canceller. A rectangular sliding window is used such that the oldest input data are replaced by the newest input data as input to the adaptive weight calculation. These weights are then applied to the newest data in the window. Throughout this study all the jamming or interference signals consist of white noise 50 dB above thermal noise. The NB and WB cases are characterized by the fractional bandwidth  $f_b$ , which is the ratio of bandwidth to center frequency:  $f_b = 0.001$  for NB and  $f_b = 0.5$  for WB. The one-jammer case was examined first, followed by an investigation of the two-jammer case.

### A. One-Jammer Case

#### (1) *Effects of Subband Weightings*

For a single jammer, the effect of different subband weightings on a BP canceller system is first investigated. Figure 6 shows the results for a 64-point FFT ( $N = 64$ ) 2-channel WB BP canceller system with different weightings for 10-pole Butterworth filter without pole error. Here, an 8-sample sliding window is used to determine the canceller weights. The inverse FFT consists of 64 time samples, and the average CR is shown for each sample. The input weightings include uniform, Tukey with  $\alpha = 0.5$  and  $\alpha = 0.25$ , Hamming, Hanning, Blackman, and Riemann weightings [7]. The parameter  $\alpha$  associated with the Tukey weighting, often called the cosine-tapered weighting, denotes the fraction of the weighting that is unity (an  $\alpha$  of 1.0 is the same as uniform weighting). It is seen that for all cases, the CR is not uniform from subband to subband and diminishes at either end. The result is that the CR averaged over the time samples will be degraded by the end points. This degradation in CR can be avoided by overlapping the input data. A 100% overlap would provide the performance indicated at the center of the curves, but at the expense of significantly increasing computational requirements. One can trade off computational intensity with cancellation performance by having some degree of overlapping. Using a 50% overlap is to use the center  $N/2$ , or 32 samples in Fig. 6, from each overlapping input batch to provide a continuous stream of output data that preserves any target signal appearing in the radar channel. From Fig. 6, it can be concluded that a reasonable compromise for a WB BP canceller system to achieve the best cancellation



performance is to use a 50% overlap with  $\alpha = 0.5$  Tukey weighting applied to the subbands. With 50% data overlap, significant enhancement in cancellation performance is achieved as the number of operations per second is doubled. The sampling interval time-bandwidth product  $T_s$  used in this simulation is 1. If  $T_s$  is allowed to vary from 0.5 to 1, there is little variation in the cancellation performance for a WB BP canceller system. With an 8-sample sliding window for canceller weight calculation, the CR is found to have a loss of 0.6 dB compared to the theoretical optimum performance. Hereafter, all the CR results are obtained for canceller weights determined from an 8-sample sliding window at  $T_s = 1$ , with uniform and/or  $\alpha = 0.5$  Tukey weightings on the subbands.

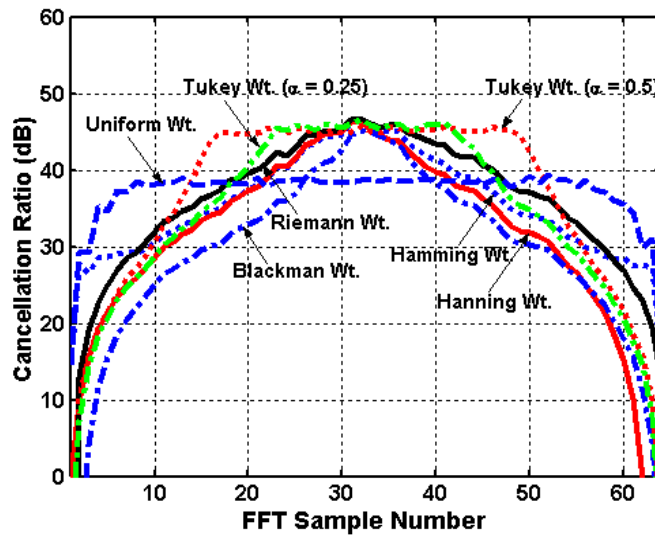


Fig. 6. CR vs FFT sample number for an  $N = 64$ , 2-channel WB BP canceller system with various weightings and no filter errors for one-jammer case.

## (2) Effects of Radar Bandwidth and Filter Mismatch Error

The effects of increasing radar bandwidth on canceller performance are examined next. Figure 7 shows the computed CR for an  $N = 32$ , 2-channel BP system as the fractional bandwidth increases with no channel filter mismatch for two different subband weightings – uniform and Tukey ( $\alpha = 0.5$ ). As expected, the CR generally degrades as the fractional bandwidth increases. The effects of main and auxiliary channel filter mismatch errors on the canceller performance are also investigated. The mismatch is achieved by randomly perturbing the pole positions of the Butterworth filters. The perturbation consists of a two-dimensional, zero-mean and uncorrelated Gaussian distribution at each pole position whose variance is specified as a percentage of the pole amplitude. Figure 8 differs from Fig. 7 in that both the main and auxiliary channel filters are independently mismatched with 5% errors. This is a severe mismatch that causes approximately 14.5 dB degradation in the NB case with Tukey Weighting ( $\alpha = 0.5$ ) and 50% data overlap. A decrease of about 10 dB occurs for the WB system with  $f_b = 0.5$ . Figure 9 shows the computed CR's for the NB and WB 2-channel BP canceller systems as the pole error increases from 0 to 10% with  $N = 32$ ,  $\alpha = 0.5$  Tukey weighting and 50% and no data overlap. In general, the CR decreases as the filter mismatch error increases. As the pole error increases, the degradation in CR is faster for the NB than for the WB system. Consequently the performance of the WB BP canceller is expected to approach that of the NB system when the filter mismatch error becomes substantially large. The benefit of data overlap is also evident for the cases with severe filter mismatch errors. The benefit of 50% data overlap over no data overlap is also evident in cases of severe mismatch errors.

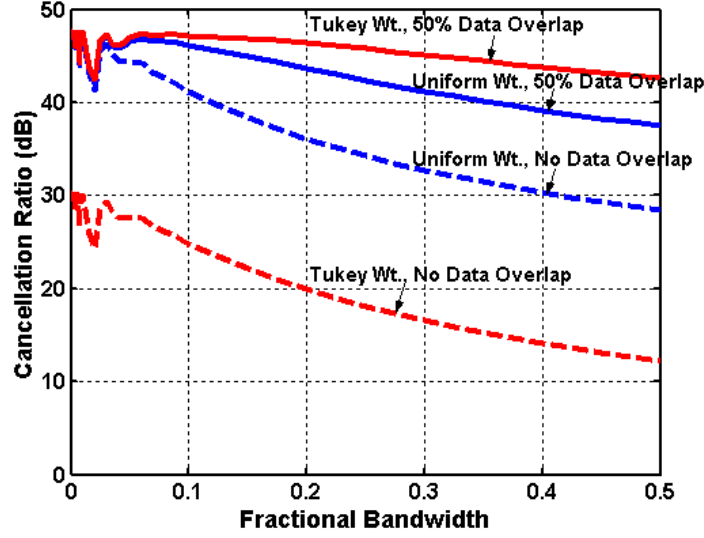


Fig. 7. CR vs  $f_b$  for an  $N = 32$ , 2-channel BP canceller system with uniform weighting and Tukey weighting ( $\alpha = 0.5$ ), 50% and no data overlap, and no pole error for one-jammer case.

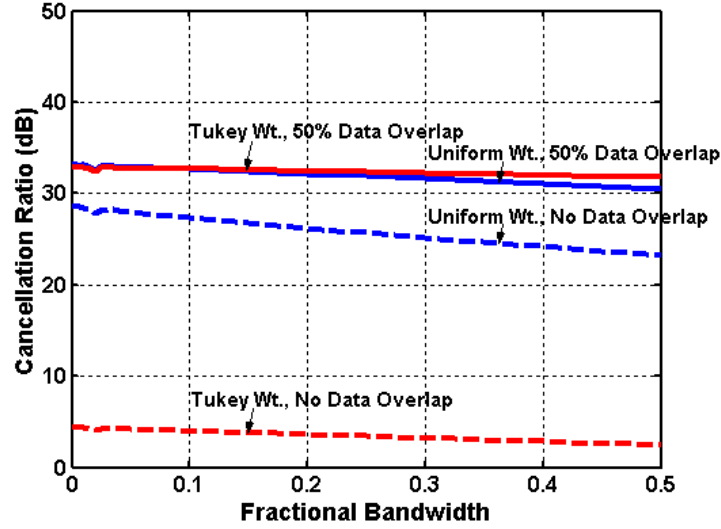


Fig. 8. CR vs  $f_b$  for an  $N = 32$ , 2-channel BP canceller system with uniform weighting and Tukey weighting ( $\alpha = 0.5$ ), 50% and no data overlap, and 5% pole error for one-jammer case.

### (3) Effects of Number of Channels and Subbands

The performance of the BP canceller system with more channels and more subbands is expected to improve. This is shown in Fig. 10 for the WB case. The advantage of Tukey over uniform weighting with increasing  $N$  is evident. The CR, plotted as a function of the total number of channels and the number of subbands  $N$ , increases as  $N$  increases, and the use of more degrees of freedom can compensate for the channel filter mismatch. For example, a BP canceller system with 5 channels and 64-point FFT can achieve approximately 48 dB of CR with  $\alpha = 0.5$  Tukey weighting and 50% data overlap for a WB system with 5% filter mismatch error. This is comparable to the CR obtained for a 2-channel NB system with no pole error. As the number of channels further increase to 20,

the CR also increases. This is illustrated in Fig. 11 for an  $N = 64$  WB BP canceller system with uniform and  $\alpha = 0.5$  Tukey weightings and 5% pole error.

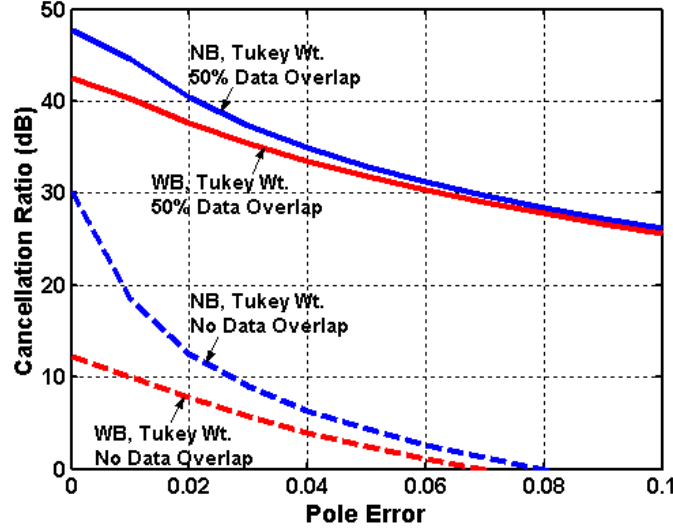


Fig. 9. CR vs pole error for an  $N = 32$ , 2-channel NB and WB BP canceller systems with Tukey weighting ( $\alpha = 0.5$ ) and 50% and no data overlap for one-jammer case.

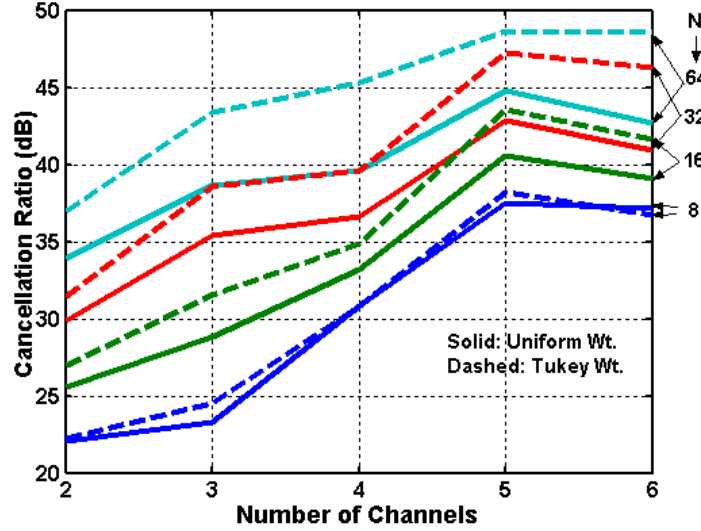


Fig. 10. CR vs. number of channels and  $N$  for WB BP canceller system with uniform weighting and Tukey weighting ( $\alpha = 0.5$ ), 50% data overlap and 5% pole error for one-jammer case.

#### (4) Effects of Multipath Time Delay

The multipath time delay is characterized by the mismatch time delay – bandwidth product  $T_m$ . For the 2-channel cases, the jamming signal in the main channel is the same as in the auxiliary channel except that it is delayed by  $T_m$ . Figure 12 shows the cancellation performance of an  $N = 8$ , 2-channel NB and WB BP canceller systems with no pole error and 5% pole error as the multipath time delay  $T_m$  varies from 0 to 1. As expected, the CR decreases as  $T_m$  increases. The difference in CR between the NB and WB systems is approximately 17.5 dB if there is no pole error and no multipath time delay. As this time

delay increases, the CR for the NB system degrades faster than the WB case. The performance at  $T_m = 1$  between two systems is about 1.5 dB. As  $T_m$  increases, the performance of the system with 5% pole error tends to approach that of the system with no pole error. The performance degradation is in fact mainly caused by the increasing multipath time delay. Figure 13 shows the cancellation performance of the corresponding NB and WB BP canceller systems with  $N = 64$ . The CR difference between the two canceller systems with no pole error is about 2.5 dB at  $T_m = 0$ . This is due to the improvement that a higher number of subbands would provide for a WB system. The cancellation performance is greatly enhanced by more subbands in the presence of multipath time delay for both NB and WB systems. However, the difference in CR when  $T_m = 1$  is near 1 dB. In the presence of pole errors, results similar to the  $N = 8$  case are found for the  $N = 64$  case in that the degradation in CR is mainly attributed to the increasing multipath time delay.

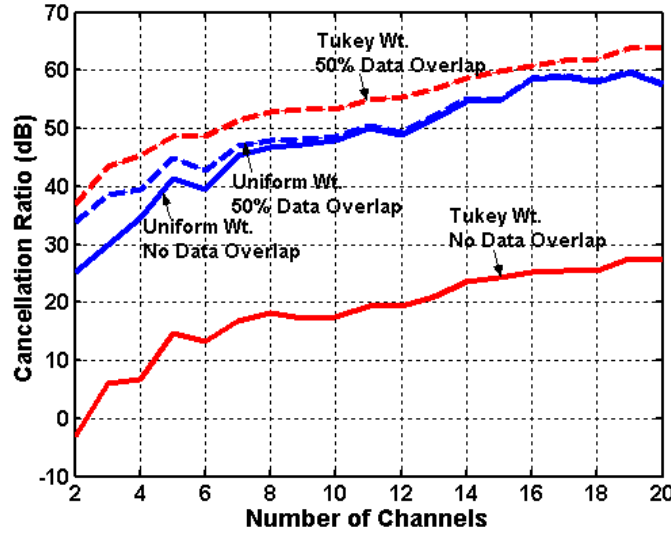


Fig. 11. CR vs number of channels for an  $N = 64$ , WB BP canceller system with uniform weighting and Tukey weighting ( $\alpha = 0.5$ ), 50% and no data overlap, and 5% pole error for one-jammer case.

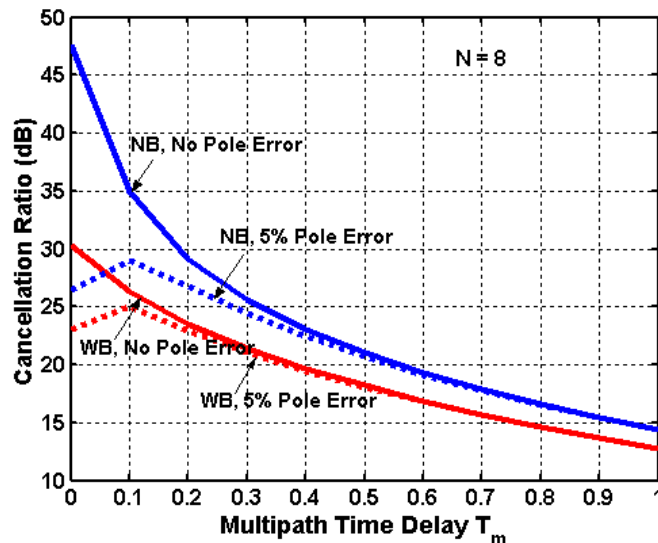


Fig. 12. CR vs. multipath time delay for an  $N = 8$ , 2-channel NB and WB BP canceller system with Tukey weighting ( $\alpha = 0.5$ ), 50% data overlap, 5% and no pole error for one-jammer case.

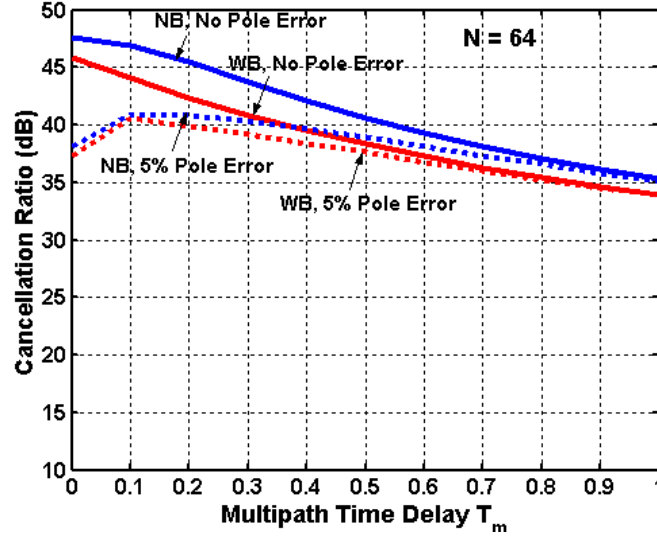


Fig. 13. CR vs. multipath time delay for an  $N = 64$ , 2-channel NB and WB BP canceller system with Tukey weighting ( $\alpha = 0.5$ ), 50% data overlap, 5% and no pole error for one-jammer case.

### B. Two-Jammer Case

Similar results are also obtained for the two-jammer case when the CR is plotted as a function of the fractional bandwidth. For the two-jammer case, at least three channels are required for proper jamming cancellation. Figure 14 shows the computed CR of an  $N = 8$  and 64, 3-channel BP canceller systems with Tukey weighting ( $\alpha = 0.5$ ), 50% and no data overlap, and no pole error. For each jammer, the jamming signal is again white noise that is 50 dB above thermal noise. As before, the CR degrades as the fractional bandwidth increases. The CR is much higher with 50% data overlap as compared with no data overlap case, especially with higher number of subbands. More improvement in CR can be achieved with more subbands for a WB system than for a NB system. Figure 15 shows that the CR increases as the number of subbands and/or the number of channels increase. These results are for a WB BP canceller system with Tukey weighting ( $\alpha = 0.5$ ), 50% data overlap and no pole error. For an  $N = 64$  8-channel WB system, very good cancellation performance comparable to the  $N = 8$ , 3-channel NB system can be achieved.

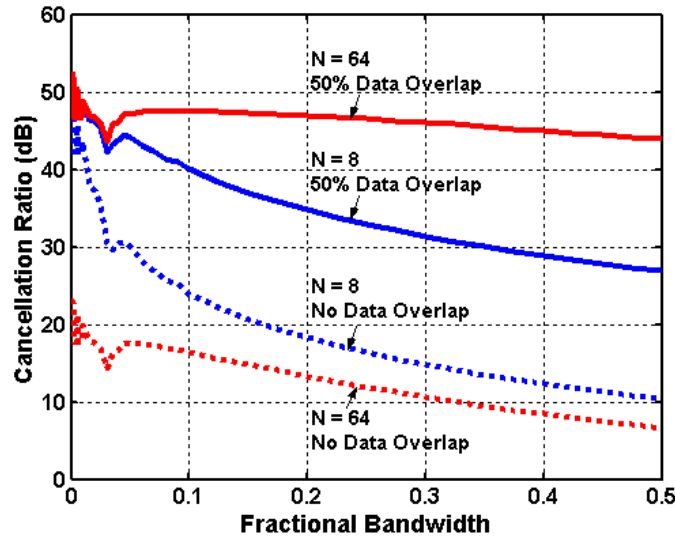


Fig. 14. CR vs  $f_b$  for an  $N = 8$  and 64, 3-channel BP canceller system with Tukey weighting ( $\alpha = 0.5$ ), 50% and no data overlap, and no pole error for two-jammer case.

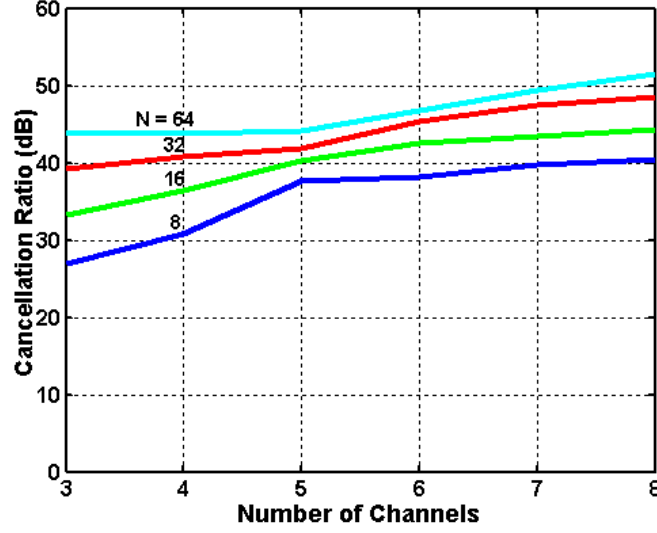


Fig. 15. CR vs number of channels with various numbers of subbands for WB BP canceller system with Tukey weighting ( $\alpha = 0.5$ ), 50% data overlap and no pole error for two-jammer case.

In the presence of multipath time delay, the jamming signals in the main and the first auxiliary channels are delayed by  $2T_m$  and  $T_m$  with respect to the second auxiliary channel, respectively. Figure 16 shows the cancellation performance of the  $N = 8$  and  $N = 64$ , 3-channel WB BP canceller system with Tukey weighting ( $\alpha = 0.5$ ) and 50% data overlap. The computed CRs for both 5% and no pole error cases are obtained. As in the one-jammer case, the performance of the BP canceller for the two-jammer case with 5% pole error approaches the case without pole error as the multipath time delay becomes more severe. The effect of multipath on CR plays a more significant role than the effect of pole error. To compensate for the performance degradation due to multipath, the hybrid configuration is investigated in the following section.

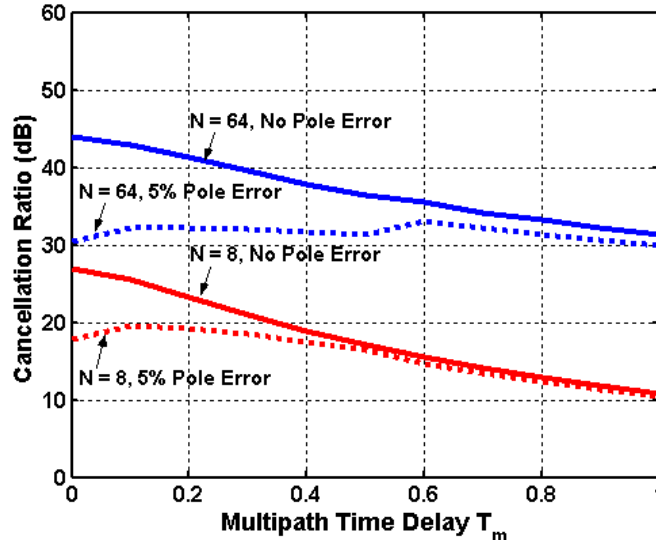


Fig. 16. CR vs  $T_m$  for an  $N = 8$  and  $N = 64$ , 3-channel WB BP canceller system with Tukey weighting ( $\alpha = 0.5$ ), 50% data overlap, and 5% and no pole error for two-jammer case.

## THE HYBRID CONFIGURATION

The hybrid configuration of the canceller system consists of BP and transversal filtering. This configuration is particularly effective in jamming cancellation if there is multipath, characterized by the time delay-bandwidth product  $T_m$  between the main and auxiliary channels. The hybrid configuration is illustrated in Fig. 17 for a single transversal filter with time delay-bandwidth product of  $T_d$  on the auxiliary channel for the one-jammer case. The main channel, the auxiliary channel, and the time-tapped auxiliary channel inputs are cancelled using the Gram-Schmidt configuration after performing an  $N$ -point FFT on each input channel, followed by an inverse FFT.

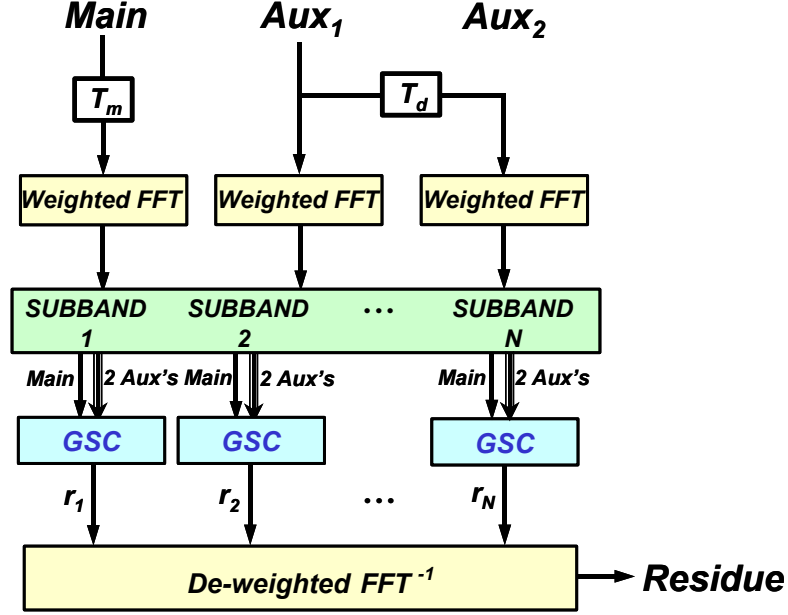


Fig. 17. A hybrid BP canceller system for one-jammer case.

It is expected that better canceller performance can be achieved when an appropriate time delay implemented on the auxiliary channel compensates for the time mismatch between the main and auxiliary channels. This is demonstrated in Fig. 18 for a NB hybrid system with  $N = 8$ , Tukey Weighting ( $\alpha = 0.5$ ), 50% data overlap and no pole error. The cancellation performance for the one-jammer case is plotted as a function of multipath time delay  $T_m$  with various transversal filtering time delays  $T_d$ . The CR of the 3-channel hybrid BP canceller with no multipath ( $T_m = 0$ ) and no transversal filtering delay ( $T_d = 0$ ) is 50 dB. The performance can almost be achieved for the hybrid configuration in the presence of multipath if  $T_d$  is chosen to be the same as  $T_m$ . For example, the CR for the 3-channel hybrid BP canceller with  $T_d = 0$  and  $T_m = 0.5$  is 21 dB. The hybrid configuration with  $T_d = 0.5$  would provide about 48 dB of cancellation performance with the same multipath time delay. Consequently, with the hybrid configuration the CR is enhanced by 27 dB.

A similar plot for a NB hybrid system with  $N = 64$  is shown in Fig. 19. With more subbands, the cancellation performance is greatly improved even though there is multipath. However, the hybrid configuration for the NB case with  $T_d = 1$  would generally provide further enhancement in cancellation performance for a wide range of multipath time delays. For example, with  $T_m = 0.5$ , the hybrid configuration with  $T_d = 1$  would yield about 11 dB improvement in CR over the same configuration with  $T_d = 0$ .

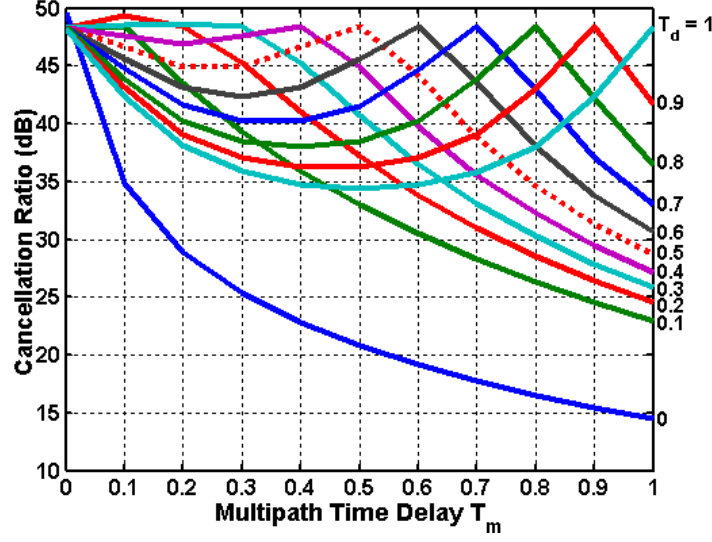


Fig. 18. CR vs  $T_m$  with various  $T_d$  for an  $N = 8$ , NB hybrid BP canceller system with Tukey weighting ( $\alpha = 0.5$ ), 50% data overlap and no pole error for one-jammer case.

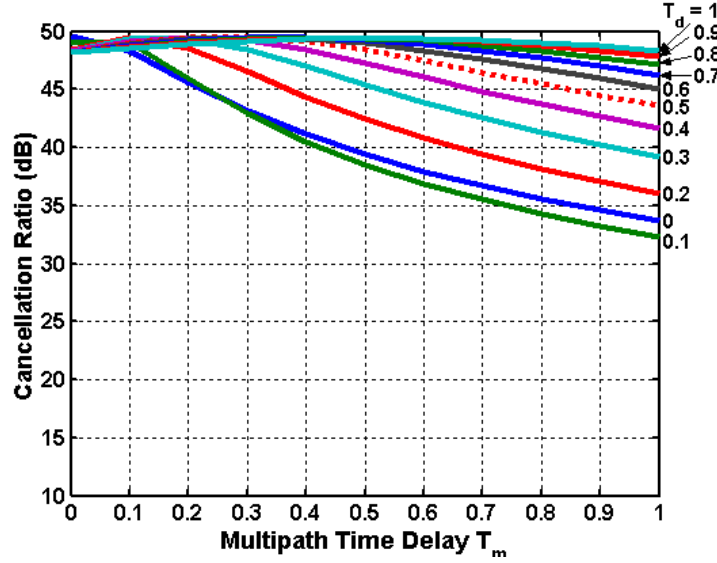


Fig. 19. CR vs  $T_m$  with various  $T_d$  for an  $N = 64$ , NB hybrid BP canceller system with Tukey weighting ( $\alpha = 0.5$ ), 50% data overlap and no pole error for one-jammer case.

Next, the effects of increasing radar bandwidth on the cancellation performance of the hybrid configuration are investigated. The CR is obtained for the  $N = 8$ , hybrid configuration with  $T_d = 0.5$  as a function of  $T_m$  when the radar fractional bandwidth  $f_b$  is increased from 0.001 (NB system) to 0.5 (WB system). This is illustrated in Fig. 20 in which the peak of each curve shifts toward a higher value of  $T_m$  as  $f_b$  increases. For the WB case of  $f_b = 0.5$ , it is shown as an example that, if a time delay  $T_d$  of 0.5 is used in the hybrid configuration, 48 dB of cancellation can be achieved for the case of  $T_m = 0$ . Similar results are also obtained for the hybrid configuration with  $T_d = 0.2$ , as depicted in Fig. 21. For the WB case of  $f_b = 0.5$  and  $T_m = 0.55$ , 48 dB of cancellation can be obtained if a time delay  $T_d$  of 0.2 is used in the hybrid BP canceller system. In general, to achieve better performance the required time delay in the hybrid configuration for the WB case of  $f_b = 0.5$  is  $T_d \approx T_m - 0.35$ .



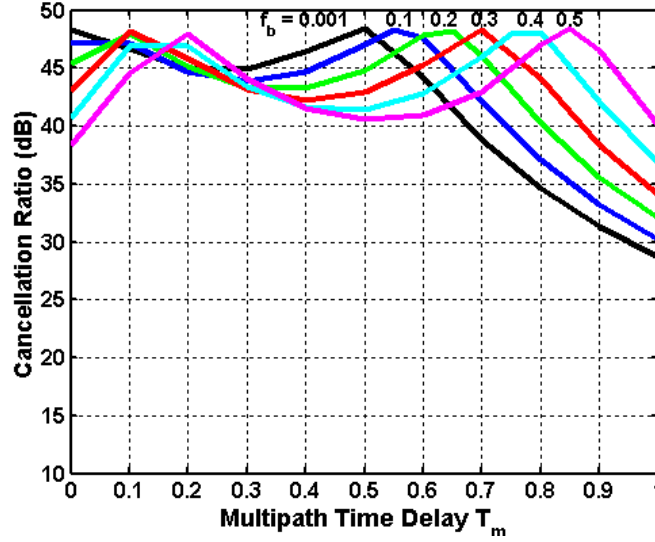


Fig. 20. CR vs  $T_m$  with various  $f_b$  and  $T_d = 0.5$  for an  $N = 8$ , hybrid BP canceller system with Tukey weighting ( $\alpha = 0.5$ ), 50% data overlap and no pole error for one-jammer case.

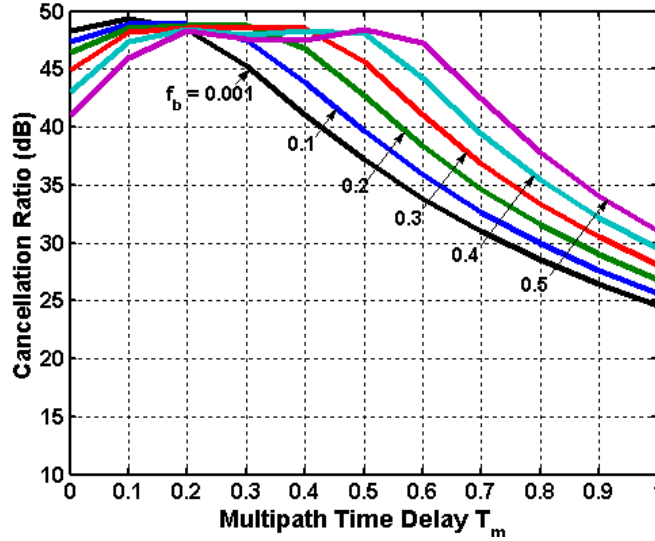


Fig. 21. CR vs  $T_m$  with various  $f_b$  and  $T_d = 0.2$  for an  $N = 8$ , hybrid BP canceller system with Tukey weighting ( $\alpha = 0.5$ ), 50% data overlap and no pole error for one-jammer case.

For the WB hybrid system with  $N = 8$ , Fig. 22 shows the cancellation performance as a function of  $T_m$  when  $T_d$  is varied from 0 to 1. Good performance can be achieved with  $T_m \leq 0.3$  when  $T_d = 0$  is used in the hybrid configuration. However, much better performance is obtained if the larger multipath time delay is compensated by a smaller time delay on the auxiliary channel, given by  $T_d \approx T_m - 0.35$  as described above. In general, a hybrid configuration can provide more improvement in those cases with higher  $T_m$  values. If the number of subbands in the WB system is much higher (e.g.  $N = 64$ ) as shown in Fig. 23, good cancellation performance is obtained if  $T_d = 1$  is implemented in the hybrid configuration when  $T_m \leq 1$ . More cancellation performance improvement is also achieved for higher  $T_m$ . Furthermore, if more subbands and  $T_d = 1$  are used in the hybrid BP canceller system, the performances of WB and NB systems are quite similar (Fig. 19 and Fig. 23).

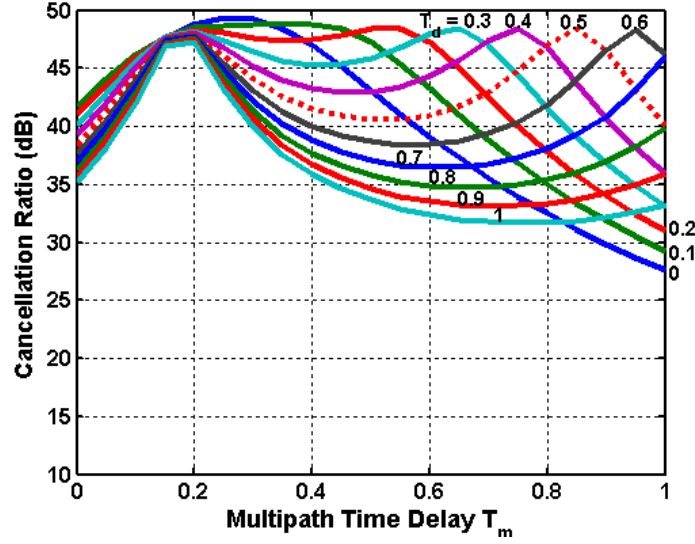


Fig. 22. CR vs  $T_m$  with various  $T_d$  for an  $N = 8$ , WB hybrid BP canceller system with Tukey weighting ( $\alpha = 0.5$ ), 50% data overlap and no pole error for one-jammer case.

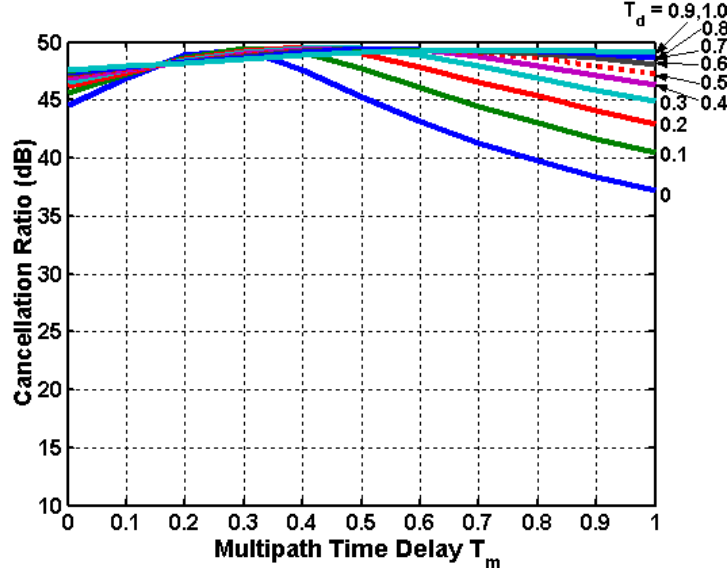


Fig. 23. CR vs  $T_m$  with various  $T_d$  for an  $N = 64$ , WB hybrid BP canceller system with Tukey weighting ( $\alpha = 0.5$ ), 50% data overlap and no pole error for one-jammer case.

In the presence of 5% pole error, the performance of a NB hybrid system with  $N = 8$ , Tukey Weighting ( $\alpha = 0.5$ ) and 50% data overlap is shown in Fig. 24. For  $T_m \leq 0.2$  the hybrid system with  $T_d = 0$  can provide CR greater than 30 dB. For higher  $T_m$ , approximately 30 dB CR can be achieved by choosing  $T_d = T_m$ . This yields an improvement over the 3-channel hybrid BP canceller system with  $T_d = 0$ . Figure 25 shows the corresponding cancellation performance of a WB hybrid system. For  $T_d = 0$  the performance of the NB hybrid system is about 13 dB better than the WB case with no multipath. When the multipath time delay increases to about 0.25, both systems have the same performance. About 30 dB CR is achievable if  $T_d \approx T_m - 0.4$  is used in the WB hybrid system for higher values of  $T_m$ . Consequently, the cancellation performance is comparable for both NB and WB hybrid configuration systems (CR = 30 dB) with  $N = 8$  and 5% pole error if appropriate delay  $T_d$  is implemented for  $T_m > 0.3$ .

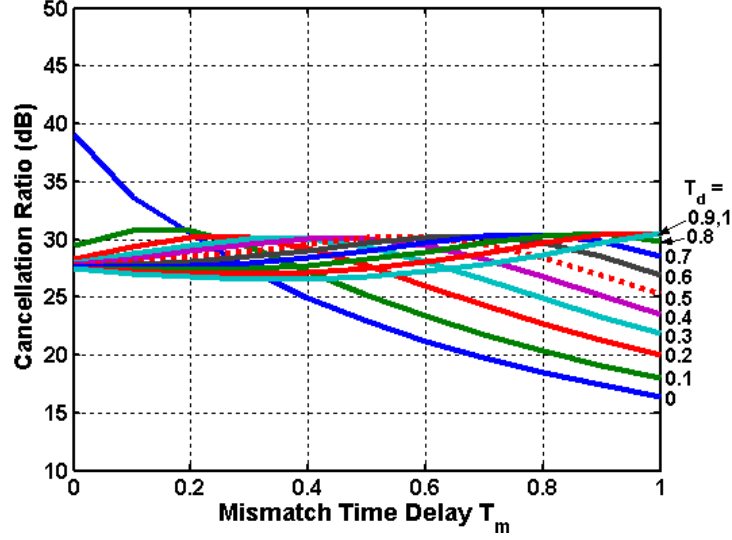


Fig. 24. CR vs  $T_m$  with various  $T_d$  for an  $N = 8$ , NB hybrid BP canceller system: Tukey weighting ( $\alpha = 0.5$ ), 50% data overlap and 5% pole error for one-jammer case

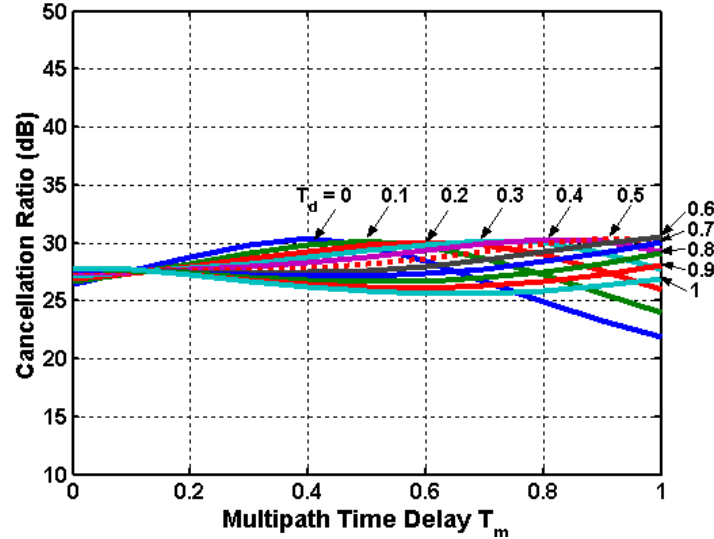


Fig. 25. CR vs  $T_m$  with various  $T_d$  for an  $N = 8$ , WB hybrid BP canceller system: Tukey weighting ( $\alpha = 0.5$ ), 50% data overlap and 5% pole error for one-jammer case

The hybrid configuration of the BP canceller system for the case of two jammers is considered next and shown in Fig. 26. Normally two auxiliary channels are needed for proper jamming cancellation in a regular BP canceller system for two jammers. If the multipath time delay  $T_m$  is present between the Main and the first auxiliary channel ( $Aux_1$ ), and between the first and the second auxiliary channels ( $Aux_3$ ), appropriate time delays  $T_d$  and  $2T_d$  are applied to the first and the second auxiliary channels, respectively, to form extra channels ( $Aux_2$  and  $Aux_4$ ) in the hybrid configuration. Consequently four auxiliary channels are required, as illustrated in Fig. 26.

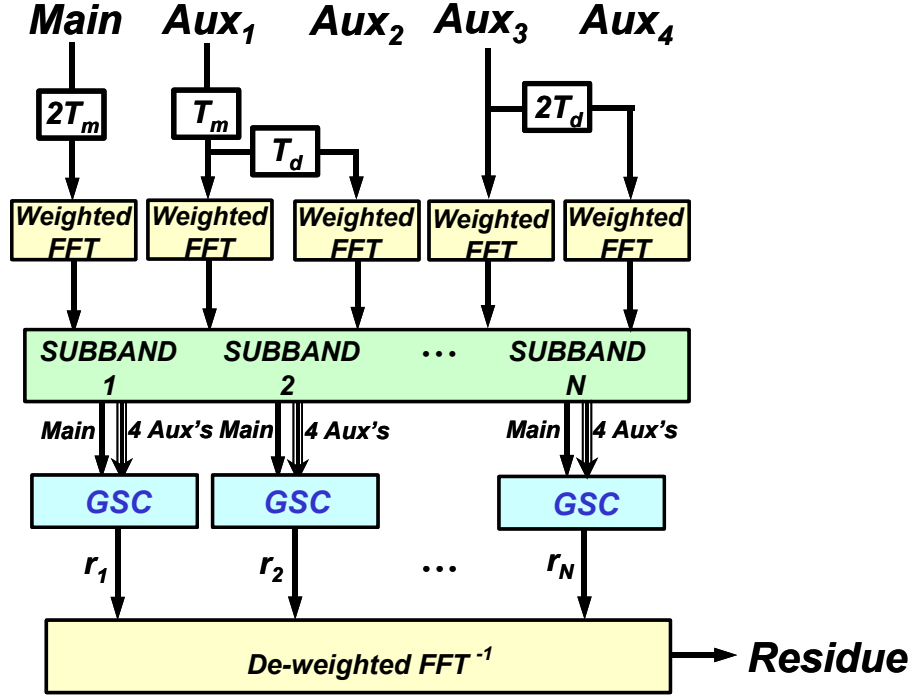


Fig. 26. A hybrid BP canceller system for two-jammer case.

Cancellation performance of the hybrid BP canceller system for the two-jammer case is obtained for a NB system with  $N = 8$ , no filter mismatch error, Tukey Weighting ( $\alpha = 0.5$ ) and 50% data overlap. Figure 27 shows the calculated CR as a function of multipath time delay  $T_m$  when various values of transversal filtering time delay  $T_d$  are used in the hybrid configuration. Similar to one-jammer case shown previously, the CR value of 54.5 dB of a hybrid 5-channel BP canceller in the absence of  $T_m$  can almost be achieved with the hybrid configuration in the presence of  $T_m$  by selecting  $T_d$  to be the same as  $T_m$ . For example, approximately 29 dB of CR is obtained with  $T_m = 0.5$  when  $T_d = 0$  is used in the 5-channel hybrid BP canceller system. The hybrid configuration with  $T_d = 0.5$  would yield about 53.5 dB in cancellation performance, an improvement of 24.5 dB. With a regular 3-channel BP canceller system, the CR is only 17.5 dB when  $T_m = 0.5$  (see Fig. 16). The significant improvement of CR for the NB system using a hybrid configuration with  $T_d = 0.5$  over the regular 3-channel BP canceller is accomplished at the expense of increasing degrees of freedom and system complexity.

As the radar bandwidth increases, the achievable cancellation performance of the above hybrid BP canceller system degrades even if  $T_d$  is chosen to be the same as  $T_m$ . This is shown in Fig. 28 for  $T_d = 0.5$  in which the CR is plotted as a function of  $T_m$  when  $f_b$  is varied from 0.001 (NB system) to 0.5 (WB system). Comparing Fig. 26 with Fig. 20 we see that for the WB two-jammer case, the CR degrades with increasing  $T_m$  for a given  $T_d$ . The peaks shown in the NB system (Fig. 20) disappear in the WB system (Fig. 28) as the radar fractional bandwidth increases. Similar results are also observed for the hybrid configuration with  $T_d = 0.2$ , as shown in Fig. 29. Consequently, the performance of the hybrid configuration for the WB two-jammer case with  $f_b = 0.5$  would be quite different from the NB system. This is illustrated in Fig. 30 where the CR, plotted as a function of  $T_m$  for various values of  $T_d$ , degrades as  $T_m$  increases. As opposed to the NB system, improved performance cannot be realized by selecting an appropriate  $T_d$  for the WB hybrid configuration when multipath exists and the radar bandwidth increases.

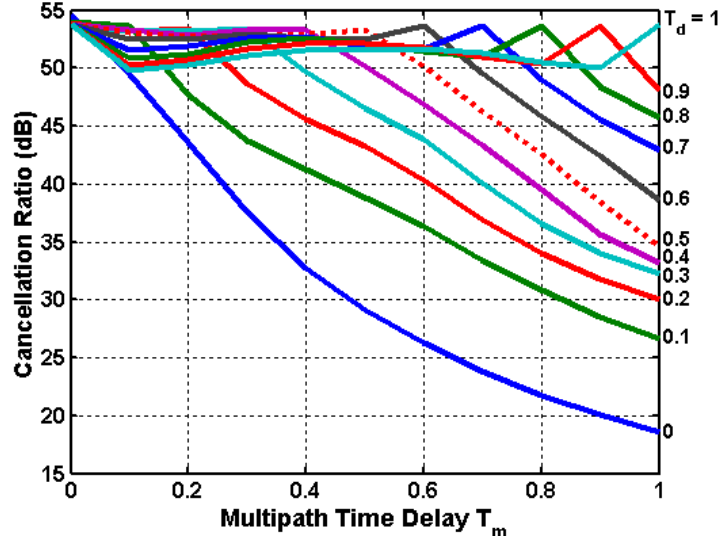


Fig. 27. CR vs  $T_m$  with various  $T_d$  for an  $N = 8$ , NB hybrid BP canceller system: Tukey weighting ( $\alpha = 0.5$ ), 50% data overlap and no pole error for two-jammer case

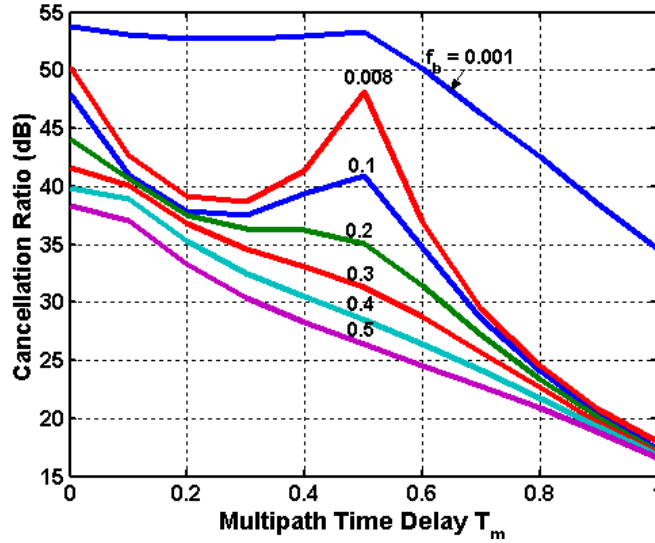


Fig. 28. CR vs  $T_m$  with various  $f_b$  and  $T_d = 0.5$  for an  $N = 8$ , hybrid BP canceller system with Tukey weighting ( $\alpha = 0.5$ ), 50% data overlap and no pole error for two-jammer case.

## CONCLUSIONS

Cancellation performance of the multiple-channel band-partitioned (BP) canceller for both narrowband (NB) and wideband (WB) systems was evaluated. Performance results were obtained for both one-jammer and two-jammer cases. Trade-off studies were conducted by varying the radar bandwidth, number of subband filters and their weightings, data overlap, filter mismatch errors, sample intervals, multipath time delays, and number of canceller channels in the multiple-channel BP canceller configurations. It was found that, in general, the cancellation performance degrades as the radar bandwidth increases. Better performance can be obtained for both NB and WB systems with the  $\alpha = 0.5$  Tukey weighting applied to the subbands and 50% data overlap than with uniform weighting and no data overlap. It was shown that the cancellation ratio decreases as the channel filter mismatches and/or

multipath time delays increase. In addition, more channels and/or more subbands in the BP canceller system would provide improved cancellation performance. Consequently, increasing the number of subbands and/or number of sidelobe-canceller channels can compensate for the degradation in cancellation performance for the WB system as the radar bandwidth increases.

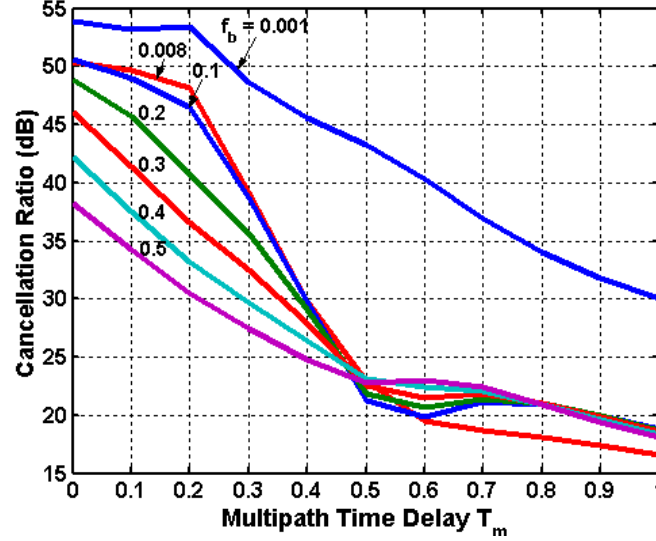


Fig. 29. CR vs  $T_m$  with various  $f_b$  and  $T_d = 0.2$  for an  $N = 8$ , hybrid BP canceller system with Tukey weighting ( $\alpha = 0.5$ ), 50% data overlap and no pole error for two-jammer case.

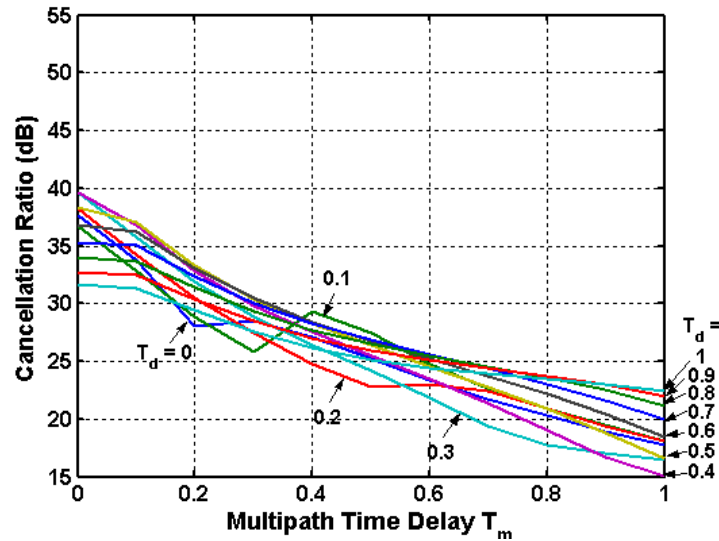


Fig. 30. CR vs  $T_m$  with various  $T_d$  for an  $N = 8$ , WB hybrid BP canceller system: Tukey weighting ( $\alpha = 0.5$ ), 50% data overlap and no pole error for two-jammer case

A hybrid BP canceller system consisting of band-partitioning and transversal filtering was also investigated. The system is found to be more effective in the presence of multipath if appropriate time delays implemented for the auxiliary channels are used as extra auxiliary channels. For the one-jammer case, the performance of a NB hybrid system with 8 subbands without multipath can be achieved for the case with multipath if the time delay used in the extra auxiliary channel matches the multipath time delay.

For the WB hybrid system, however, near optimum performance can be realized for large multipath time delay if the time delay in the extra auxiliary channel is chosen to be less than the actual multipath time delay. The difference between the multipath time delay and the time delay implemented in the auxiliary channel depends on the radar bandwidth. For the two-jammer case, the NB hybrid BP canceller system performance is quite similar to the one-jammer case. However, the performance of the WB hybrid system degrades as the multipath time delay increases and the performance degradation cannot be compensated with the time delays in the auxiliary channels as radar bandwidth increases.

A combination of using a proper number of subbands, subband filter weighting, data overlap, and sufficient degrees of freedom provide an excellent balance between processing complexity and performance for a WB BP canceller system. For the one-jammer case, the hybrid configuration in general provides significant cancellation performance improvement if appropriate time delay is used in the auxiliary channel for a given multipath delay. However, this performance enhancement is accomplished at the expense of more degrees of freedom, and increasing system and processing complexity. The methodology used here can be applied to the WB adaptive beamforming problem for the compensation of frequency-dependent mismatch such as channel filter mismatch effects, aperture frequency dispersion, and effects of multipath and finite array propagation delay.

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